



**Middeck Glovebox (MGBX)**

## **Internal Flows in a Free Drop (IFFD)**

**Glovebox Investigator:**

**Dr. Satwindar S. Sadhal  
University of Southern California  
Los Angeles, California**

## INTERNAL FLOWS in FREE DROPS (IFFD)

E.H. Trinh <sup>1</sup>, S.S. Sadhal <sup>2</sup>, D.A. Thomas <sup>3</sup>, and R.K. Crouch <sup>4</sup>

<sup>1</sup> Jet Propulsion Laboratory

<sup>2</sup> University of Southern California

<sup>3</sup> Astronaut Office, Johnson Space Center

<sup>4</sup> NASA Headquarters, Washington DC

### ABSTRACT

Within the framework of an Earth-based research task investigating the internal flows within freely levitated drops, a low-gravity technology development experiment has been designed and carried out within the NASA Glovebox facility during the STS-83 and STS-94 Shuttle flights (MSL-1 mission). The goal was narrowly defined as the assessment of the capabilities of a resonant single-axis ultrasonic levitator to stably position free drops in the Shuttle environment with a precision required for the detailed measurement of internal flows. The results of this entirely crew-operated investigation indicate that the approach is fundamentally sound, but also that the ultimate stability of the positioning is highly dependent on the residual acceleration characteristic of the Spacecraft, and to a certain extent, on the initial drop deployment of the drop. The principal results are: the measured dependence of the residual drop rotation and equilibrium drop shape on the ultrasonic power level, the experimental evaluation of the typical drop translational stability in a realistic low-gravity environment, and the semi-quantitative evaluation of background internal flows within quasi-isothermal drops. Based on these results, we conclude that the successful design of a full-scale Microgravity experiment is possible, and would allow accurate the measurement of thermocapillary flows within transparent drops. The need has been demonstrated, however, for the capability for accurately deploying the drop, for a quiescent environment, and for precise mechanical adjustments of the levitator.

### 1. BACKGROUND

The fundamental importance of thermocapillary (or Marangoni) flows in a low-gravity environment has been firmly established by many theoretical and experimental investigations [1-3]. It is also clear that the rigorous separation of these surface tension-driven flows from buoyant convection is not achievable in a ground-based laboratory when the additional requirement for accurate velocity field measurement is also imposed. Although a substantial effort has been expended by NASA in the study of Marangoni convection in recent years, little work has been devoted to the case of a totally free, three-dimensional liquid-gas interface such as that presented by freely levitated drops. The recently developed experimental techniques for drop levitation has allowed the acquisition of notable new understanding in scientific subjects in fluid dynamics, surface phenomena, and fundamental material science [4-9]. Access to low-gravity allows the most effective exploitation of this levitation-based experimentation approach because it allows the drastic reduction of the detrimental influence of the high-intensity fields required for levitation against 1-G.

The side effects of levitation fields in Earth-based laboratories are the principal subjects our ground-based research task: The outer streaming flows and the induced internal circulation associated with ultrasonic levitation are investigated, and their impact on the measurement of thermocapillary flows is to be assessed. In addition, experimental measurements of buoyant thermocapillary flows in laser-heated electrostatically levitated drops are to be carried out in 1-G in order to develop the techniques for Microgravity implementation. The opportunity to develop and to carry out a preliminary Glovebox

investigation should lead to the generation invaluable new information for the planning and development of a potential flight experiment.

Even though our Earth-based experimental studies utilize electrostatic levitation, this approach is quite elaborate and no proven technique has yet been tested for operation in Microgravity. Ultrasonic levitation, on the other hand, is a mature technology, and it has been demonstrated to operate equally well on Earth and in microgravity. This latter method also has the advantage to require a modest level of instrumentation, and has been shown to be relatively simple to operate. A major deficiency, however, arises from the uncontrolled drop rotation which has been attributed to the induced streaming flows associated with high-intensity sound waves. The goal of the Glovebox investigation is thus to test a single-axis resonant ultrasonic levitator in low-gravity by measuring the residual uncontrolled drop rotation under minimal power level and using adjustable mechanical controls in an isothermal condition as well as under differential heating.

The specific objectives are then defined as:

- The demonstration of the feasibility of using a simple non-contact single-axis ultrasonic positioner to study thermocapillary flows in low-gravity.
- The evaluation of the interfering effects due to ultrasonic levitation forces.
- The measurement of the drop equilibrium shape and residual rotation as a function of the acoustic power level
- The performance of the first experimental observation of thermocapillary flows in a free drop due to non-uniform surface heating (this objective was not carried out on STS-94 or 83, but it will be implemented for a reflight on STS-95).

## 2. EXPERIMENT DESCRIPTION

The test for the non-contact positioning of a drop in microgravity was carried out by using an ultrasonic resonant levitator [5] operating at 23 kHz. Manual tuning of the resonance conditions was performed by adjusting both the frequency of the electronic drive as well as the mechanical gap separation for optimizing the standing wave intensity. The levitator was designed to fit on an optical assembly also used to hold a diode laser and beam expander and a solid-state photodetector with focusing lens assembly. **Figure 1** shows the IFFD apparatus components. The entire optical assembly is placed on the work area inside the Glovebox, but both the Electronic Control Unit (ECU) and the laser battery packs remain outside. The Glovebox doors remain open except for the front one which holds the front view video camera. A second video camera is mounted on the Glovebox panel in order to display a top view of the drop through a window placed in the reflector component of the ultrasonic levitator. Internal flow and rotational motion of the drop are observed through suspended tracer particles dispersed in the test liquid (Pliolite tracers particles).

A drop is manually injected and deployed inside the levitation region using a syringe and either Teflon or steel needle. Drops of water and an aqueous solution of glycerin with diameter between 2 and 4 mm were deployed during the flight. The adjustable sound field parameters were the drive frequency and the amplitude. The analog electronic instrumentation was custom designed and has previously flown as a part of the STS-50 science payload in 1992.

The data to be acquired are:

- The drop video images (providing a measurement of the diameter and shape deformation using the calibration image of a ruler),
- The motion of the suspended particles inside the drop (providing the internal flow and the rotation rate),
- The ultrasonic power level.
- Video data are recorded on the Glovebox 8mm VCR tapes



**Figure 1. IFFD flight investigation apparatus**

### 3. EXPERIMENTAL PROCEDURE

The most crucial part of the experimental procedure is the manual drop injection and deployment process. This is primarily because manual tuning of the standing wave is required prior to injecting a drop from a syringe and needle assembly. The process involves both frequency setting on the electronic control module and the mechanical adjustment of the spatial gap where the ultrasonic standing wave is established. The visual feedback for the quality of the resonance tuning is provided by the distortion of the droplet by the ultrasonic radiation pressure.

After successful deployment of a free drop within the levitation volume, a waiting period is required for sample stabilization. A rough alignment of the mechanical components of the levitator is required for optimal sample stability. In addition, at low ultrasonic drive power the restoring force of the acoustic well is diminished, and a minimization of all external continuous and transient acceleration is required. For typical Earth-based conditions, the resonant translation mode of a 3 mm diameter drop in the acoustic well has a frequency in the vicinity of 40 Hz. In low gravity this resonance would

be on the order of 5 Hz; any disturbance with a similar frequency component would drive oscillatory motion.

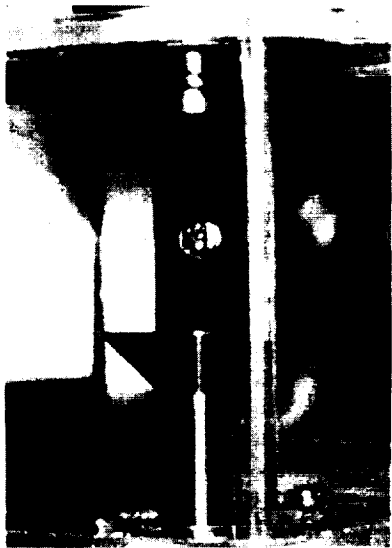
Limited adjustment of lighting using the 1.1 cm diameter diode laser beam and the Glovebox internal lights is required for optimization of both the drop contour for shape and dimension measurements, and for the visualization of the suspended tracer particles. Adjustments to the front and top view Glovebox video cameras are also required for sharp focus and centering of the drop image.

The determination of the controlling parameters for the minimization of the uncontrolled drop rotational motion requires the adjustment of micrometers setting the relative alignment of the driver and reflector components of the ultrasonic levitator. *The principal objective of the investigation is to establish the minimum required acoustic power for stable sample positioning and the measuring the resulting minimum rotational velocity.* Once those conditions are obtained, observation of the internal flow through suspended particle tracking can be accomplished.

#### 4. EXPERIMENTAL RESULTS

##### 4.1 Drop Translational Stability

Drops of water and water-glycerin mixtures with diameter between 0.2 and 0.6 cm have been deployed and restrained within the ultrasonic positioning well. Once the drop positioning controls are adjusted for optimum and quiescent conditions in the Spacelab module, the sample translational oscillations have been observed to be restricted to excursions *smaller than*  $0.1 R_{DROP}$  for low acoustic power and spherical equilibrium shape. Because of the smaller required field of view, this kind of positional stability allows a high enough optical magnification to resolve the details of the motion of tracer particles within the drop bulk with a *relative position resolution of better than 0.5 %*. The Sound Pressure Level (SPL) required to keep 5 mm diameter drops stationary within this restricted excursion window is *45 dB lower* in the microgravity environment than in 1-G.

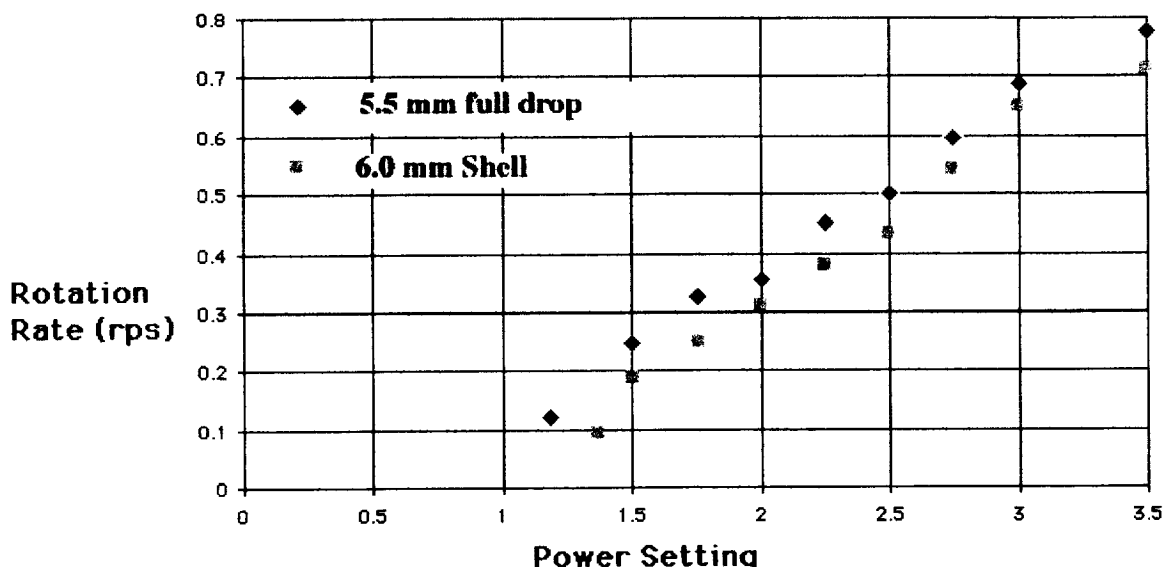


**Figure 2: A positioned drop in the IFFD in  $\mu G$ .**

##### 4.2 Drop Rotational Stability

The IFFD ultrasonic levitator incorporates a cubical chamber surrounding the immediate drop trapping volume. The primary purpose for this transparent lucite enclosure is to shield the drop from external forced convection, but the hard, acoustically reflecting walls also introduce extraneous resonances that interfere with the primary positioning standing wave. This cavity also shapes the acoustically-driven convective flow fields which generate the aerodynamic torque on the freely levitated drop. The characteristic convective (or streaming) velocity is proportional to the square of the acoustic pressure amplitude, and a substantial uncontrolled drop rotational motion results due the aerodynamic drag exerted by the air flow on the drop surface. A limited control over the direction and magnitude of this resulting aerodynamic torque can be exercised by making fine mechanical adjustments of the relative alignment of the reflector and acoustic driver components of the levitator. A drastic reduction of the convective velocity, however, can be directly effected by reducing the acoustic pressure. The above mentioned decrease in the required microgravity positioning acoustic power also greatly lowers the uncontrolled drop rotational velocity.

**Figure 3** reproduces the data obtained from the residual rotational velocity on a 4.5 mm diameter glycerin-water drop and a 5.1 mm diameter thick glycerin-water-air shell (drop with a suspended air bubble). As observed, a minimum rotation rate of 0.1 rps can be measured at the lowest acoustic drive levels in both cases. The residual rotation rate measurements were carried out after all mechanical alignments of the reflector and driver have been effected by the crew. These adjustments have invariably resulted in setting the drop rotation axis in a plane normal to the levitator symmetry axis, yielding a rotation roughly normal to the front camera viewing axis



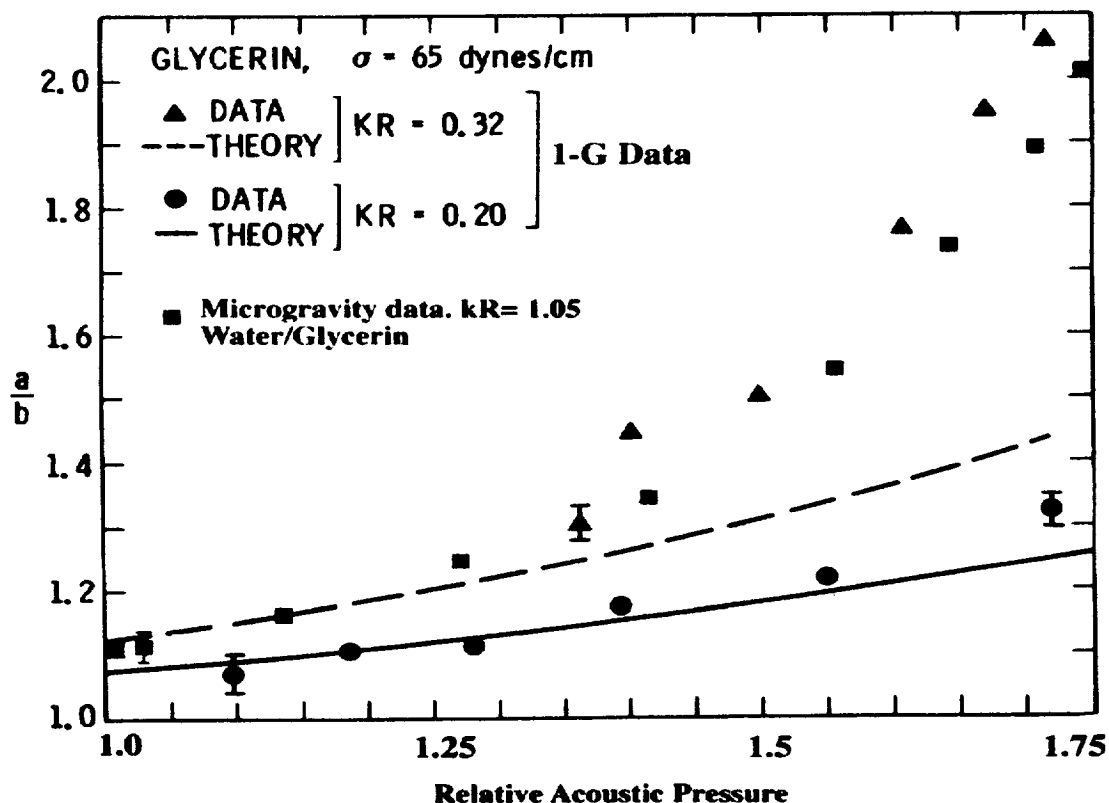
**Figure 3.** Residual rotation rate as a function of the acoustic power

#### 4.3 Controlled Drop Deformation Measurements

Because the drop is positioned at an acoustic pressure nodal plane in microgravity, it becomes feasible to carry out detailed measurement of the *symmetrical* acoustically-induced drop deformation in order to perform a quantitative evaluation of existing theoretical predictions. It also becomes possible to carry out measurement at very low acoustic pressure and for *electrically uncharged* free drops. A quantitative validation of

theoretical treatments will allow their use in the development of reliable non-contact methods for the measurement of surface tension of viscous liquids which do not allow measurements of dynamic oscillations.

The STS-94 data yielded drop deformation with axial ratio ranging between 1.0 (spherical drops) to 2.3 (drastically flattened drops). The linear dimensions of the drop contour could be determined to better than 0.5 %, allowing a relative accuracy of better than 1% for the drop axial ratio. **Figure 4** displays results of the low-gravity measurements together with Earth-based data. The axial ratio is plotted as a function of the relative change in acoustic pressure level for both ground-based [10] and microgravity data. In addition to extending to very low relative acoustic pressure, the low-gravity data show a larger deformation for the same acoustic pressure ratio. The droplet size relative to the acoustic wavelength was larger in microgravity than on Earth ( $kR=2\pi R/\lambda=1.1$ ). The range of the measurements has been greatly extended in microgravity both for droplet size and deformation (both at the high and low deformation values).



**Figure 4.** Measurement of drop deformation as a function of the acoustic pressure amplitude.

#### 4.4 Residual internal flow in a quasi-isothermal drop

A state of very slow drop rotation has allowed the measurement of the residual internal flow within freely positioned droplets in a quasi-isothermal environment. Such a

measurement is required in order to determine the base state within the drop prior to inducing thermocapillary flows using spot-heating. The analysis of three different sets of video images for three different drops has resulted in a quantitative evaluation of the average residual convective flow within free drops in microgravity. The data indicate that any residual convection velocity could not be greater than 0.05 mm/minute. These results were obtained by using two-camera tracking of visible tracer particles within droplets undergoing slow rotation under minimal acoustic drive.

## 5.0 SUMMARY

An unbiased assessment of the results of the IFFD flight investigation would be generally positive: All of the objectives have been addressed and conclusive and reliable data have been obtained. The practical capabilities of a simple single-axis drop levitator have been reasonably well tested in the Shuttle environment, and some conclusive evidence for the feasibility of performing accurate thermocapillary flow measurements in the moderate Marangoni number region has been obtained. Very low acoustic power is required for stable positioning, leading to negligible drop deformation and a low residual rotation rate. In addition, the first set of data on acoustically-induced drop deformation has been obtained in low gravity, under conditions which make it feasible to compare with theoretical predictions.

The scope of a Glovebox investigation significantly limits the resources and sophistication needed to design and to implement a well controlled flight experiment. The lack in capabilities for full automation and intelligent control of the experiment, however, can be compensated by the availability of skilled operators. The IFFD investigation was designed for complete flexibility for manual control and adjustment to unanticipated observations. The intent was to test the experimental approach, but also to document the various details associated with the unpredictable behavior of a free drop within an ultrasonic restraining force potential. We believe that in spite of the difficulty encountered during operations of the experiment, substantial new knowledge has been acquired that will allow the design of a more substantial and automated apparatus that would be a useful and productive containerless experimentation facility for fluid dynamical studies.

## ACKNOWLEDGMENTS

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